The University of Chicago

A Study of the Purkinje Phenomenon with Spectral Lights

A DISSERTATION

SUBMITTED TO THE FACULTY
OF THE GRADUATE SCHOOL OF ARTS AND LITERATURE
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF PSYCHOLOGY

BY
ETHEL MARY CHAMBERLAIN

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS
1911

The University of Chicago

A Study of the Purkinje Phenomenon with Spectral Lights

A DISSERTATION

SUBMITTED TO THE FACULTY
OF THE GRADUATE SCHOOL OF ARTS AND LITERATURE
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF PSYCHOLOGY

BY

ETHEL MARY CHAMBERLAIN

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS
1911

ACKNOWLEDGMENTS

To all those, both professors and students, who by their kindly assistance made this investigation possible, we offer our hearty thanks. Our greatest indebtedness is to Professor James R. Angell for never-failing interest and practical aid, to Dr. Harvey A. Carr for valuable advice and criticism, to Dr. John B. Watson for the use of his apparatus, and to the subjects, who gave willingly of their time and energy in the performance of a somewhat tedious experiment.

CONTENTS

I. INTRODUCTORY STATEMENT

The present study of the Purkinje phenomenon grew out of a desire to work over, with the use of reflected spectral lights, the field which had already been covered many times by experimenters who used pigments or direct spectral lights. The paper will first briefly review the work which has been done by these investigators. This will be followed by a discussion of brightness criteria and their relation to this problem. The experiments performed in the course of the investigation will be described and their results analyzed, and the paper will close with a formulation of the conclusions derived therefrom. The experiments here described were performed during the academic year, 1910–11, and the historical sketch and bibliography cover the period ending Jan. 1, 1912.

The Purkinje phenomenon may be provisionally defined as the changes in color and brightness undergone by the spectrum when its light-intensity is diminished during total or partial dark-adaptation of the eye of the observer. These changes are roughly describable as a relative darkening of the less refrangible end of the spectrum and a relative brightening of the more refrangible; that is, the brightest point in the spectrum shifts from yellow to the region of the green.

II. HISTORICAL SKETCH

A. INVESTIGATION AND THEORY

The first experimenter to publish data on the comparative brightness of spectral colors was J. Frauenhofer (18) in 1817. These measurements were taken quite incidentally in the course of an investigation of the refractive and dispersive power of different kinds of glass for use in telescopes. He used a bright sunlight spectrum and obtained results on the basis of which he drew an intensity curve which is still used in text-books of physics. His results show that the brightest place in the spectrum lies between the D and the E lines, with the other lines arranged as follows in order of diminishing brightness; F, C, B, G, H.

More than fifty years later, von Vierordt (60) published a curve which almost coincided with that of Frauenhofer.

The first statement of the changes in color and brightness brought about by alterations in the light-intensity of colors and by accompanying changes in the state of adaptation of the retina, was made by Purkinje (55) in 1825. Accordingly the phenomenon, including both color and brightness changes, was named after him. His investigation was uncontrolled, and consisted of the examination of pigment colors during the increasing light-adaptation of the eye caused by the oncoming of light at dawn. His description runs as follows: "Objectiv hat der Grad der Beleuchtung grossen Einfluss auf die Intensität der Farbenqualität. Um sich davon recht lebendig zu überzeugen, nehme man vor Anbruch des Tages, wo es eben schwach zu dämmern beginnt, die Farben vor sich. Anfangs sieht man nur schwarz und grau. Gerade die lebhaftesten Farben, das Roth und das Grün, erscheinen am schwärzesten. Das Gelb kann man von Rosenroth lange nicht unterscheiden. Das Blau was mir zuerst bemerkbar. Die rothen Nüancen, die

sonst beim Tageslichte am hellsten brennen, nämlich carmen, zinnobar und orange zeigen sich lange am dunkelsten, durchaus nicht in Verhältnisse ihrer mittlern Helligkeit. Das Grün erscheint mehr bläulich, und seine gelbe Tinte entwickelt sich erst mit zunehmenden Tage."

It is evident that the color aspect of the phenomenon was the striking thing. Starting from this point, later investigators have enlarged the scope of the term, so that at present the brightness aspect occupies a more important place than the color. We find no further reference to the matter in the writings of Purkinje, and the problem seems to have lain undisturbed for a quarter of a century, when it reappears in an article by Dove (12) in 1852. He studied the phenomenon with a stereoscope and drawings made in different colors, and attempted to explain it on the basis of summation of stimuli.

Helmholtz (21) published, in 1860, the first piece of experimentation made with spectral lights. His results show that the less refrangible colors are brighter in the stronger lights and the more refrangible are brighter in the weaker lights. Moreover, this difference in brightness is least marked when the colors compared come from the less refrangible end of the spectrum, is greater when they are chosen from the more refrangible end, and is greatest when they come from different ends. These results were incorporated in a curve of brightness distribution of the spectrum.

To test the validity of this curve, Dobrowolsky (11), in 1881, made some experiments and published his results, together with a criticism of Helmholtz' work. His findings differed somewhat from those of the latter, and the two sets are not strictly comparable on account of differences in method and in the colors employed.

Lepinay and Nicati, in 1882 (47), attacked the problem by the visual acuity method, with the following results: (1) The Purkinje phenomenon does not exist for rays less refrangible than $507\mu\mu$; (2) When the objective intensity of the light is varied, the visual acuity for blue increases and decreases more slowly than for the less refrangible rays. The

writer questions the value of this work on the ground that it is not an established fact that visual acuity depends entirely upon the amount of light received by the eye.

Brodhun (4), in 1887, published results from three subjects, one with normal vision, one a protanope, and the third a deuteranope. He employed the Helmholtz color-mixing apparatus. The curves for the normal subject and the deuteranope displayed the phenomenon from the violet end to 570 $\mu\mu$, but in wave lengths higher than this it failed to appear.

Up to this point, the emphasis had been laid on the descriptive side of the matter, but from about 1885 on, the tendency was to search for an explanation. Experimenters realized that it was one of the most important facts which must be explained by color theory.

In connection with the study of this problem, Hering (23) developed his theory of the white valence of colors. This conception was used and elaborated by Hillebrand, who added to it his theory of the specific brightness of colors (25). The latter was eventually accepted by Hering.

Hering (24) worked more than ten years upon the determination of the white valence of the various colors, and upon this evidence based an explanation of the Purkinje phenomenon which he embodied in his paper upon the investigation of a totally color-blind subject. He also worked upon the hypothesis that the brightness of a given color is made up of its white valence plus its brightening or darkening power. Upon this theory he thought it reasonable to expect to find the spectrum of the totally color-blind coinciding with the spectrum as seen by the normal eye below the color limen. As a matter of fact, he satisfied himself that this was the case. The brightest point for his color-blind subject was in the region of 524$\mu\mu$.

We question the value of a generalization about white valence based upon results from a color-blind person. Why should a subject who is abnormal in the chromatic aspect of a color necessarily be normal in the achromatic? Unless he were normal in the latter case, the evidence is useless.

At about this time, König (30) published an account of an extended piece of work with a deuteranope, a protanope, and two subjects with normal vision. He used a modified form of the Helmholtz color-mixing apparatus. Embodying his results in curves, he found that those of the dichromats were very similar to those of the subjects with normal vision. He felt that his curves definitely displayed the Purkinje phenomenon, although he admitted that his results were in no way final.

Hering, in a paper published in 1895 (22), expresses his intention of arranging certain disorganized facts about the Purkinje phenomenon for the benefit of future students. He calls attention to two misapprehensions in regard to the character of the phenomenon, which had been prevalent in the minds of experimenters up to that time. Helmholtz and his school concerned themselves only with color and brightness changes. In other words, they assumed that a change in intensity of the lights themselves was the only method of bringing about this result. With the introduction of the concepts of white valence and specific brightness, it began to be evident that there might be other factors than those recognized by Helmholtz. König's experiments are valuable except for the fact that he disregards, in the main, the important rôle played by the condition of adaptation of the eye.

To Hering's mind, there are three methods of obtaining the phenomenon: (1) Diminution of the light-intensity of colors, accompanied by partial or complete dark-adaptation of the eye; (2) Unchanged light-intensity of colors, accompanied by momentary dark-adaptation, (a) of both eyes, (b) of one eye, the other being continuously dark-adapted; (3) Changing the stimulated area on the retina. Hering defines two grades of dark-adaptation. One he styles "momentary" and describes it as the change in the condition of the whole visual organ brought about by sudden darkening. "Continued adaptation" is the condition resulting from the gradual oncoming of twilight or slow artificial darkening. Method (3) is based upon the assumption that from the center of the retina toward the periphery the sensitivity to white relatively in-

creases, while the sensitivity to colors relatively decreases. Therefore the act of moving a color toward the eccentric portion occasions the Purkinje phenomenon.

Hering calls attention to the fact that Helmholtz and his followers believed that the phenomenon occurred as a simple result of the decreasing of the light-intensity of the colors. He himself demonstrated that this is not the only condition. He found that if he kept the subject's eyes light-adapted by having the room in which he sat in full illumination, he might decrease the light-intensity of the colors as much as he liked without any change in their relative brightness. It is important to remember that this statement refers only to central vision and does not involve the problem of peripheral vision.

The two possible factors in the production of the phenomenon are; (1) decrease of light-intensity, (2) change in the condition of adaptation of the eye. It appears from Hering's experiment that the adaptation factor may act independently of the light-intensity factor, but that the latter, acting alone, is incapable of producing the same effect. This is an aspect of the problem which was overlooked by his predecessors.

Ebbinghaus (13), in his description of the phenomenon, says that with diminishing light-intensity red, green, and bluish violet spread over the spectrum at the expense of the other color tones. Finally the three displace all others, and, separated only by very small intermediary zones, lie close together. This fact was not reported by our observers. For them the colors merely faded out in their own positions, giving place to grays of different brightnesses. Red was the only exception, and it could be seen as color down to the brightness threshold, displaying no photochromatic interval.

The "visual purple" theory, upheld chiefly by Parinaud, von Kries, and Ladd-Franklin, has been advanced as an explanation of the Purkinje phenomenon. Visual purple is a substance which exists on the retinal rods. It is objectively purple in color, bleaching to yellow by the action of light upon it. It is more sensitive at low light intensities than at high ones, and it reinforces faint-light vision by absorbing some of the light

which would otherwise pass through the transparent rods. On account of its color, it absorbs green light most readily and blue next. These colors are reinforced in terms of white light to such an extent that they are the brightest colors in the spectrum at low illumination, while they are comparatively lacking in brightness at high illumination. In the latter case the visual purple is less sensitive and does not perform its reinforcing function. This reinforcement accounts for the photochromatic interval in all colors except red, for visual purple is not sensitive to this color. And it is known that red does not possess a photochromatic interval.

The main arguments in favor of the "visual purple" theory as an explanation of the Purkinje phenomenon are: (1) it is based upon retinal structure; (2) the phenomenon is alleged to be absent in the fovea, which is destitute of rods and therefore of visual purple; (3) the absorption spectrum of visual purple from the extirpated human eye has the same brightness arrangement as the faint-light spectrum; (4) exposure of one eye to the light does not bleach the visual purple of the other. The Purkinje phenomenon may be observed with one eye and not with the other, according to the condition of adaptation of the eyes.

The "visual purple" theory has been criticised on the ground that the length of time required for bleaching and regeneration does not correspond with the length of time required for the oncoming and breaking up of dark adaptation. Also some experimenters maintain that the phenomenon is present in the fovea.

(B) RELATION OF THE PURKINJE PHENOMENON TO THE FOVEA

No observations were made upon the existence of the phenomenon in the fovea until 1895 when Parinaud (51) in France and von Kries (35) in Germany, independently of one another, discovered its absence in that area. The main interest of each was in determining whether or not the rods are involved in the production of brightness sensation. Von Kries, after

experimentation with spectral lights, asserts that the Purkinje phenomenon does not occur in the fovea.

Sherman (58) states that von Kries later discovered two errors in his work, but that his belief in the matter remained the same.

Koster (33) measured the rodless area of the retina, and his experiments show the existence of the phenomenon within this area. Von Kries criticises him, saying that he did not use sufficient care in fixation.

In 1898 Sherman (58) pursued an investigation with gelatine sheets, and convinced himself that the phenomenon occurs in the fovea just as it does in other parts of the retina and under the same conditions.

Von Kries and Nagel (40) investigated the matter with pigment colors and were unable to find it in the fovea. Tests were made with subjects having normal vision, and also with three deuteranopes. They observed that a slight wavering of fixation threw the image outside the fovea and produced the Purkinje effect.

In viewing such contradictory results obtained by dependable experimenters, it must be remembered that: (1) authorities differ as to the exact dimensions of the fovea, and (2) no subject can hold a perfectly steady fixation; and consequently in some cases the image may have fallen on the paracentral area.

(c) THE PURKINJE PHENOMENON IN INDIRECT VISION

Hering (22) devotes a section of his paper to the relation of the phenomenon to indirect vision. The white sensitivity of the retina, he says, increases from center to periphery, while the color sensitivity decreases. Then in moving a stimulus from center to periphery of the retina of the dark-adapted eye, we have practically the same result as that obtained by decreasing the light-intensity of the color. Thus the Purkinje phenomenon should result, and as a matter of fact it does appear. As the eye approaches a condition of complete dark-adaptation, the effect is heightened.

Peters (52) worked on the periphery of the dark-adapted retina, using colored gelatine sheets. His results are as follows: (1) In the paracentral region, red and yellow decrease in brightness in the lower intensities, and green and blue increase; (2) After the minimum of brightness is reached in red and yellow, a brightness increase clearly takes place, which on the edge of the visual field gives place to a new decrease in yellow. Blue and green show a decrease after the maximum of brightness has been reached, the latter being greater in green than in blue; (3) The characteristic brightness decrease for red and the increase for blue stretch further toward the periphery in the left meridian than in the others. The maximal brightness lies in the vertical lower meridian.

(D) THE EXTENDED PURKINJE PHENOMENON

Ebbinghaus and Ladd-Franklin (42) observed at about the same time, but independently of one another, that the phenomenon is operative in cases where color quality has disappeared. If two grays, made of complementary colors, match in brightness in full illumination, they differ in brightness in low illumination with the dark-adapted eye. Then the mixture having the higher white valence is the brighter. Ladd-Franklin named this the Extended Purkinje phenomenon.

After making a series of experiments with spectral lights, von Kries revised Newton's law of color mixing to read, "Equations which are valid for high intensities are incorrect with dark adaptation and the diminution of light-strength, in the sense that the mixture which has the greatest rod-valence (white valence) contains a surplus of colorless brightness."

(E) RELATION OF COLOR QUALITY TO BRIGHTNESS OF BACKGROUND

It has been suggested that brightness of background may be one of the factors involved in the phenomenon, but the literature which deals with the relation of background to color tone gives no clear evidence of this.

Baird (3) gives the results of an investigation of the periphery of the dark-adapted eye with transmitted lights in a completely

dark room. He found that under these conditions, which were practically those of an absolutely black background, the following color changes occurred: red appeared usually as red, sometimes as orange, occasionally as brown or gray; orange was orange or yellow or infrequently reddish or gray; yellow was usually yellow or orange, sometimes gray; green was always green, yellow, or gray, blue was blue or gray.

G. M. Fernald (15) (16) published two papers on the relation of brightness of background to colors on the peripheral retina. With the darker backgrounds red appeared as orange or yellow, orange as yellow or yellow-orange, green as yellow-green or yellow. With the lighter grounds red appeared as red, orange was also red, yellow was orange, green was uncertain. Results for blue were unsatisfactory. Thompson and Gordon (59) arrived at practically the same results with the same apparatus.

From the above results it appears that brightness of background has comparatively little effect upon the color quality of the colors at the blue end of the spectrum, while it affects those at the other end. Red, yellow, and orange tend toward red on a light background and toward yellow on a dark.

(F) GENERAL SUMMARY

1. The Purkinje phenomenon includes both color and brightness changes resulting from certain conditions.

2. There are probably at least two factors in its production; (a) change in objective light-intensity, (b) condition of adaptation of the retina.

3. Several explanatory theories have been brought forth, none of which is entirely adequate.

4. Experimenters differ upon the question of the existence of the phenomenon in the fovea.

5. The phenomenon may be obtained by moving the stimulated area from center to periphery of the retina. Dark adaptation heightens this effect.

III. EXPERIMENTAL INVESTIGATION

(A) FORMULATION OF THE PROBLEM

The purpose of this investigation was to observe the changes brought about by decreasing the intensity of a Nernst light spectrum which was reflected from a white surface to the eye of the observer. These changes were; (1) in color quality, (2) in brightness.

The results were obtained under the following conditions; (1) central vision, with (a) dark-adapted eye, and (b) light-adapted eye. (2) Peripheral vision, with dark-adapted eye.

The investigation differed in several particulars from those previously made by others.

1. Reflected spectral light was used. Others had employed direct spectral rays which are very fatiguing to the eye.

2. Relatively large lighted areas were compared. The areas used by others were the size of the ocular of a spectroscope.

3. The type of apparatus employed made it possible to make peripheral judgments with great ease. Peripheral tests have heretofore ordinarily been made with pigments alone.

4. The experiments were performed by six observers, all possessing normal vision. Previous experimenters had only one or two normal subjects, whose results were compared with those of persons with abnormal vision.

(B) APPARATUS

The apparatus consisted of (1) the spectral light apparatus for obtaining beams of light of the required wave length and throwing them on the surfaces from which they were reflected to the eye of the observer, (2) two episcotisters for cutting down the intensity of the beams, (3) two plaster of Paris plates which acted as reflecting surfaces for the two beams.

(1) Spectral light apparatus.

The spectral light apparatus was a form of the one built at the University of Chicago in 1908 by Dr. John B. Watson, and used by him in his work on the color discrimination of monkeys. (Reported in J. of Comparative Neurol. and Psychol. Vol. 19, No. 1, April 1909.)

The source of the light, N, (Fig. A) was a Nernst glower 3.8 cm. long, requiring a current of .6 amperes. It was run on the 220 volt circuit from the university power house. An ammeter and a voltmeter showed deviations in current and potential difference, and on the few occasions when fluctuations occurred, no tests were made. Thus the entire series of experiments was carried on with a constant current flowing through the lamp. A Nernst filament of this type lasts long enough

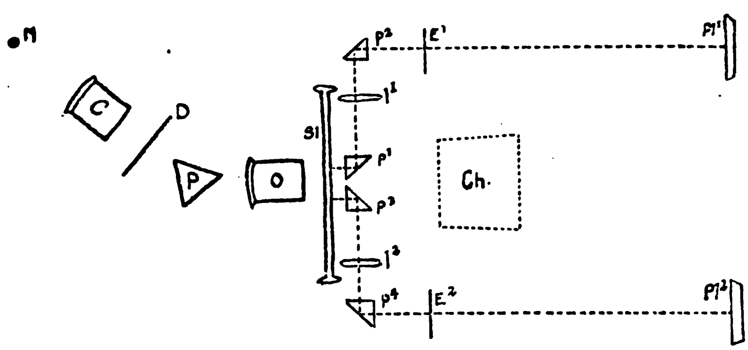

Fig. A. Apparatus

to allow all the experimentation to take place well within the life of a single filament. The filament was narrow enough to act as a slit, so the usual slit between source and collimator was not required.

The collimator lens, C, was an achromatic portrait lens with a diameter of 8.9 cm. and a focus of 20.3 cm. This was placed at its focal distance from the source. Immediately following the collimator, and screwed to the wooden frame which supported it, was the iris diaphragm, D, with which the size of the bundle of rays coming from the collimator could be regulated. The area of the opening could be varied at will between 176.5 mm² and .78 mm², and its value could be read

by means of a pointer travelling over a scale which was marked off in degrees and half degrees.

The large prism, P, which produced the spectrum, was a 60° prism of dense flint glass which has a refractive index of 1.65. The prism had a 6.3 cm. edge, and was mounted on a levelling device.

The objective, O, was an achromatic photographic lens of 8.9 cm. diameter and 25.4 cm. focus. This was placed 10 cm. from the face of the prism from which the beam emerged.

At the focal point of the objective was placed the double slit, Sl. This is described in full by Watson in his article, which contains a cut giving a horizontal view of the slit. Two jaws made of polished steel were controlled by a micrometer screw. Two smaller jaws, also of polished steel, could be moved by hand. The spectrum fell upon the steel surface, and any desired portion of it could be let through the knife-edge openings between the jaws. The position and width of these openings were accurately determined by a micrometer screw, which read to $\frac{1}{1000}$ of a millimeter. In place of the piece of black cardboard used by Watson to cover the opening, we utilized strips of metal, bent at the ends in such a way as to fit over the projecting upper and lower edges of the slit. These metal strips were also used instead of the smaller jaws in cases in which we desired to make use of two portions of the spectrum which lay closer together than the width of the jaws.

Just beyond the double slit, and supported by the iron framework which held it, were four total reflection prisms and two lenses. Each of these was mounted on an iron post which slid laterally in ways, and could be clamped in any desired position therein. Prisms p^1 and p^3 were placed by the experimenter, for each of the readings, directly in the paths of the two beams as they came through the double slit. They were 90° prisms of crown glass, with one .9 cm. edge; and these, as well as p^2 and p^4 were mounted on levelling devices which fitted into the supporting posts.

A lens, l^1 stood at the left of p^1, and a similar lens, l^2, stood at the right of p^3. These were single achromatic lenses, with a

diameter of 5.6 cm. and a focus of 12.7 cm. Each time new beams were used, the lenses were placed in such positions that they focussed the beams on the surfaces of Pl^1 and Pl^2.

The prisms, p^2 and p^4, completed the system, p^2 standing at the left of l^1, and p^4 at the right of l^2. They were 90° prisms of crown glass with a 2.5 cm. edge. They stood 35.5 cm. apart, and were not moved during the course of the experiment.

Suppose, for example, that an experimenter wishes to compare two beams, one green and the other red. The rays issuing from the narrow filament of the source are made parallel by the collimator C, pass through the circular aperture of the diaphragm D, and fall upon the face of the large prism P. They are refracted by the prism, and the spectrum thus formed is focussed by the objective, O, on the face of the double slit. The experimenter then chooses two beams of the required wave length, which he allows to pass through the two slits, a and b. Then p^1 must be set directly in front of slit a, through which the green beam is coming. The beam strikes p^1 and is reflected 90° to the left. L^1 then focusses the image on the surface of p^2 so that it travels in the same direction it took before entering slit a, and falls upon Pl^1, the reflecting plate. In the same manner the red beam is reflected to the right by p^3 and falls upon Pl^2.

The entire system was enclosed in a wooden box which was light-tight, and lined with black velvet to prevent reflection. Two holes were cut in the front of the box 35.5 cm. apart, through which the rays issuing from p^2 and p^4 passed. The box was raised on legs to the height of 66 cm. above the floor. All the lenses and prisms in the system were mounted on adjustable supports, but before the experimentation began they were screwed tight to the bottom of the box, making a rigid system, with the exception of p^1, p^3, l^1, and l^2. It was necessary to change the position of these in order to reflect the beams chosen, but the changes in no way interfered with the quality or brightness of the lights used.

(2) Episcotisters

An episcotister was placed in the path of each beam shortly

after it emerged from the box (E^1 and E^2). These were run by the same motor, and the belt was so arranged that they could be operated simultaneously or independently of one another as the experimenter wished.

(3) Reflecting plates

Two plaster of Paris plates, Pl^1 and Pl^2, stood directly in the path of the beams, 360 cm. from the point at which each emerged from the last prism in the system. These were alike and stood upright so that the beams fell upon them and were reflected back from their surface to the eye of the observer. The reflecting surfaces measured 14.3 cm. vertically and 2.5 cm. horizontally. The plaster of Paris was 2.5 inches thick, and was moulded about an upright metal rod which was supported on a tripod 87.6 cm. above the floor. The tripods holding the two plates were clamped by a connecting rod to prevent displacement, and stood 35.5 cm. apart. The plates were made of clean dentist's plaster of Paris, moulded in the shape of a slab of the dimensions given above, and knife-edged on both sides. The reflecting surfaces were then sandpapered until no inequalities were visible. These plates were covered except when in use to keep them free from dust.

The observer's chair, Ch, was placed between the beams as they emerged from the episcotisters, and was of such a height that the beams passed on either side of the subject's head at a level slightly below his eyes. The approximate distance from his eye to the plates was 233 cm. As he sat in this chair, in the darkened room, he saw two brilliant patches of color, suspended, as it were, side by side in the darkness. No background was visible, so there was no difficulty with contrast effects.

An apparatus of this kind possesses certain advantages over the type of instrument in which the observer's eye looks directly into the beam.

1. Results gained from light reflected from a surface are more comparable with results from pigments than are those derived from direct inspection of the beam.

2. The colors spread over a larger surface and are thus easier to compare than in the direct vision apparatus.

3. The lights are far enough away from the subject to make accommodation easy.

4. Judgments may be made with either monocular or binocular vision.

5. The lights are less intense, and there is no danger of injury to the eyes.

6. Peripheral judgments may be made by the use of a simple device.

7. Central comparisons can be made, for the strips of light are far enough apart to allow one to be fixated and the other disregarded. When one is being fixated, the other lies far enough out upon the periphery of the retina so that it does not interfere materially with the judgment of the color under fixation.

The experiments were performed in a large dark room which could be lighted at will from out of doors. In the series in which the subject's eyes were kept light-adapted, a curtain, of dull black opaque cloth was hung back of the plaster plates to form a black background. Then a window at the side of the room and behind the black curtain was opened in order to let in the daylight. The light-adaptation work was done on slightly cloudy days, so that the room was illuminated by diffuse daylight and not by the direct rays of the sun. Even then there was a noticeable variation in the amount of illumination from day to day, and to compensate for this the curtains were spread wider on brighter days, to bring the part of the room in which the observer sat into deeper shadow. This was a rough method, but it served the purpose, which was to bring out the differences between the results from a distinctly light-adapted eye and those from a completely dark-adapted one.

(c) SUBJECTS

Seven persons served as subjects. Of these, A., H., P., and Hu. were men; C., F., and W. were women. A., C., F., H., and W., had completed three or more years of graduate work in

psychology, P. was in his second, and Hu. was in his first year. Five of these, A., C., F., H., and P. had had from one to three years' experience as subjects on a problem in brightness discrimination between pairs of the same colors, and all had previously done some work of this kind. The vision of all the subjects was tested by means of the Holmgren wools and the Hering apparatus for the detection of color blindness. No variations from the normal were discovered.

(D) METHOD

The experimentation was divided into three groups of tests, the preliminary, the foveal, and the peripheral. The preliminary tests were carried on in the dark room with the eyes partially dark-adapted. The foveal tests comprised the main body of the work and consisted of a dark-adaptation and a light-adaptation series. The peripheral tests were made with dark-adaptation.

The four colors used were: red, 6600-6320 $\mu\mu$; yellow, 5870–5645 $\mu\mu$; green, 5225–5095 $\mu\mu$; and blue, 4780–4690 $\mu\mu$. These were chosen arbitrarily by the writer, who selected a portion of color of the desired width from the part of the spectrum which seemed qualitatively the most distinctly red, yellow, green or blue, as the case might be. The wave lengths were determined by the use of a spectrometer, which had previously been calibrated for the hydrogen, helium, mercury, sodium, and lithium lines, and a curve plotted from the results. The beam, the wave length of which was to be determined, was allowed to pass through the spectrometer, and its limits were read off on the scale. These readings were then drawn in on the curve which gave the wave length. On account of the rigidity of the spectral light system there should, theoretically, be no change in the wave length of the beams used. However, to make sure that no change had taken place, the wave lengths of the beams were read off on the spectrometer from time to time during the course of the experiment.

(1) Preliminary experiments

The preliminary experiments were of two kinds. The first

was an inspection of the spectrum as a whole under conditions of changing intensity. This was accomplished by decreasing and increasing the beam of light by means of diaphragm D. With the light from the source at its highest intensity, the entire spectrum was thrown upon a screen of white pasteboard. The subject was instructed to indicate the brightest point and to observe any changes which might take place in brightness or color quality. The operator then slowly closed the iris diaphragm until it had reached its narrowest opening, 1 mm. in diameter, and as slowly opened it again to its full width. The subject described the shift of brightness which had taken place and the order in which the colors disappeared and reappeared.

The second type of preliminary experiment consisted of several of the central vision tests given for the sake of practise. These were performed without complete dark adaptation and the results were not utilized.

(2) Main experimentation

For the main experiments of the series the operator selected three light-intensities; No. 1 in which the diaphragm was open to its full width, No. 3 with a very narrow diaphragm opening which brought the spectrum below the color limen, and No. 2 midway between the two.

(a) Experiments in central vision

These were experiments in which the middle points of the patches of color, as they appeared on the plaster plates, were successively fixated. For convenience' sake these will be called foveal experiments, but it is to be clearly understood that "foveal" refers only to the general position of the stimulated area on the retina. It does not mean that the image falls entirely within the fovea.

(1) Dark-adaptation series

The observer was seated in the chair and blindfolded with a bandage made of cotton wool covered with soft black silk. This was adjusted so as to cause as little pressure as possible

upon the eyeball, for such pressure was often followed by flight of colors. The bandage was worn for twenty minutes to insure complete dark adaptation. During this time the operator set the diaphragm at No. 1 and projected the two colors to be compared upon the plaster plates, allowing the beams to pass through open sectors in the episcotisters, which were at rest. The bandage was then removed, and the subject was asked to make a judgment as to which of the two colors was less bright than the other. This established the one chosen as the "standard" color, the other being the "comparison" color. The task of the observer was to cause the experimenter to change the intensity of the comparison until it was judged of equal brightness with the standard.

The subject was told to close his eyes and the experimenter made ready for the test. Allowing the episcotister, through the open sector of which the standard color was passing, to remain stationary, he closed the sectors of the other until the sum of the open sectors was 10 degrees. That is, when this episcotister was set in motion, the other remaining still, there appeared upon one plate 360 degrees of the standard color and upon the other 10 degrees of the comparison color, mixed with 350 degrees of black, as the episcotister revolved.

The observer was then given his instructions. He was told to formulate for his use his own standard of brightness, and to adhere to it throughout the experiment, unless he, at any time, found it to be a false one. Should this occur, he was asked to notify the operator of his change in standard and of any subsequent alterations. He was instructed to open his eyes at the "ready" signal and to fixate the center of each patch of color in turn, starting with either, and continuing the examination as long as was necessary to make a judgment. Care was to be taken to center his attention upon the color fixated and to avoid peripheral comparisons as much as possible. His judgment was to be put in terms of the comparison color, expressed as "too bright," "too dark," or "equal." After he reported his judgment he closed his eyes while the opening in the comparison episcotister was changed. These increments were not uniform,

but ranged from two to twenty degrees, as the experimenter desired. This difference was made in order that the subject might not depend, even subconsciously, upon producing equality by a given number of increments. The changes in size of opening were made in the dark, guided only by touch. The process was continued until the judgment "equal" was given. At this point the bandage was replaced, and the operator read the size of the opening in degrees, expressing the result in the form of an equation, as "360° B = 140° R."

The subject then wore the bandage for three minutes, to overcome the slight light adaptation which his eyes had undergone while observing the colors. The lights were never brilliant, even at No. 1, so the change in adaptation caused by them must have been very slight. The next tests were made with the same pair of colors, but the series alternated between "up" (starting with the color too dark) and "down" (starting with it too bright). This was done to overcome the tendency of some subjects to "overshoot" the equality point, and the equally marked habit, formed by others, of stopping short of equality.

Several practise series were taken at the beginning of every sitting, and whenever the pair of colors or the intensity of a given pair was changed. After this the regular series were continued until five "up" and five "down" were reported by the subject as satisfactory. Any inaccuracy of judgment due to the wandering of attention or some external disturbance might cause the series to be thrown out. Ten satisfactory series constituted a group, which contained the judgments on a given pair of colors at a given intensity. An entire group was completed before another was begun, and the three groups, representing the three intensities of a pair of colors, were finished before starting upon another pair.

In every case, the dark adaptation series of any pair of colors was completed before the light adaptation series for the same pair was commenced.

The time error was eliminated by instructing the observer to alternate in his fixation of the two colors, beginning sometimes with one, sometimes with the other.

Owing to the fact that in the form of apparatus used by us, the position of the colors could not be reversed, we were unable entirely to do away with the space error. The very nature of the Purkinje phenomenon helped us here, however, for while the less refrangible end of the spectrum was brighter at the higher intensity, the other end proved brighter in the lower stages. Therefore, the comparison color was sometimes on the right and sometimes on the left.

(2) Light adaptation

The light adaptation series were carried on in the manner described above except that light from out of doors was let into the room. No rest between series was required because the eyes did not have to be restored to dark adaptation. The group of tests for intensity No. 3 had to be omitted under conditions of light adaptation, because the light in the room was strong enough to obliterate the faint lights on the plates.

(b) Peripheral experiments

In order to observe the relation of peripheral to foveal judgments, a group of peripheral tests for one pair of colors at the three intensities was made by each subject, always with the dark adapted eye.

It was deemed best to place the fixation point either above or below the colors in order that it might lie at an equal distance from each. A 1 candle power electric lamp was enclosed in a small box, in the cover of which a pinhole had been made and then covered with white paper, making a dim point of light. This box was placed above and between the two plates and could be raised and lowered at will.

The limits for the colors used were established roughly as follows. The fixation point was placed 40 cm. above the tops of the plates. The experimenter placed strips of cardboard in front of the last prisms in the system, cutting off both beams. The subject was then requested to remove the bandage and fixate the pin hole. At a "ready" signal the colors appeared and the subject, still holding his fixation, stated whether or not he could see any color in the patches of light. In this

way, the fixation point was established just outside the limit of the color zone, for each pair of colors. The angular distance between fixation point and colors was measured with a large protractor, and it varied with different pairs of colors and different observers, between 16° and 22°.

The experiment then proceeded as before except that the subject held his fixation point throughout. The colors were never displayed until he had taken his fixation, and they were covered as soon as he had made his judgment, so that in most cases the subject was ignorant of the identity of the colors used.

(E) BRIGHTNESS CRITERIA

Two questions in regard to the method of judging the relative brightness of colors are open to debate.

1. Can different colors be accurately compared in regard to their brightness?

2. What should be the criterion in judging the comparative brightness of two colors?

(1) *Reliability of brightness comparisons between lights of different colors*

This is a topic upon which there has been much difference of opinion. Helmholtz (21, p. 428) says that the brightness of two different intensities of the same color may be compared with much accuracy, but that brightness comparisons between two different colors are exceedingly difficult to make. Trustworthy results may be obtained only when the two colors differ greatly in brightness. Experimenters who make many comparisons of this kind probably attain a greater accuracy through experience, but he himself always felt a great degree of uncertainty when called upon to compare two different colors in brightness. On the other hand, he felt that he was quite accurate in his judgments of small color differences with the same brightness, or small brightness differences in the same color.

König (27, p. 144) remarks in this connection that different colored fields can unquestionably be compared in brightness

to a certain extent, but that it is impossible to obtain the same accuracy as in the comparison of fields of the same color.

Ebbinghaus, on the other hand (13), considers it entirely possible to make accurate brightness comparisons between colored lights. He advises the observer, in order to acquaint himself with the concept of brightness, to compare colored lights with grays.

Langfeld (46), at the outset of an experimental paper, asserts that he feels that he and his subjects are able to make adequate brightness matches between different colors. There may be a few cases, he thinks, which are comparatively inaccurate, but on the whole, he has confidence in the method.

At the beginning of our investigation we instructed our subjects to select a brightness criterion and adhere to it in their comparisons as long as they considered it adequate. Very early in the course of the experiment, they began to question their criterion. "I select, in my first judgment in the series," says one subject, "what strikes me as a good match in brightness. I then keep a memory image of this and make all other matches in the series as near like that as possible. Even if I consciously try to ignore this, and make every match afresh, I think I approximate the standard of my first judgment without realizing it." Another remarked, "I could be satisfied with any one of half a dozen settings in that particular region. I merely choose one, and the others reproduce this more or less accurately." One reported that he made his judgments entirely without reference to any preceding ones, but that he felt quite sure that any two judgments for the same pair of colors would be practically the same. Another said, "The standard which I choose in the beginning rules my judgments for the series."

Introspectively, the writer would agree that the matches are variable within certain limits, and that the standard set at the beginning of any particular series tends to govern the series through the memory image. To this statement, we wish, however, to add another. This uncertainty of judgment is limited in its range on the brightness scale, and the tendency of

some colors to brighten and that of others to darken with changes of intensity, is operative over a far wider range than this. Consequently, although our results may be somewhat variable, we think that they are more than adequate to convince one of the existence of the Purkinje phenomenon.

(2) *Brightness criteria*

The second question now calls for attention, "What is to be the criterion in the judgment of the relative brightness of two colors?"

Langfeld, in the paper previously quoted (46), makes a valuable statement concerning two types of criteria for judging brightness. He worked with both colored papers and spectral lights, and found his standards useful in both cases. In using one standard, he attended to the amount of light which proceeded from the colored object. With the second criterion he asked himself, "Is the one or the other color nearer white?", and tried to regulate the brightness so that they would both appear to be at the same distance from white. In connection with this, he used what he calls his "solidity" standard. Yellow for instance, seemed to be a much thinner color and was judged brighter than red. He found that his subjects were using both types of standard indiscriminately in their judgments, so he asked them to use one for a certain period and then the other. He then tabulated the results from the two standards separately and found, in all but one subject, a regular relation between standard and results. The values for the judgment of equality by the second standard, color tone, were much darker than those by the luminosity standard.

Our subjects were not told of Langfeld's criteria, but were asked to formulate their own, with the result that theirs were much like his, although stated in a different fashion.

The luminosity standard was utilized by P., C., A., H., and in part by W. P. says, "In all the judgments I have ever made, I have differentiated brightness from intensity. Intensity is the extent to which it hits my eyes, (the 'push' behind it). The more intense color seems to make a deeper impression on my

retina. Brightness is luminosity—the extent to which one could read a newspaper by it. I could translate this into terms of white light if it were necessary." Others describe it as the extent to which each color, introduced in a given amount into a room of a certain size, would illuminate it. They quite commonly speak of the ease with which one could read by it.

F. used the whiteness standard throughout. She judged the brightness by the apparent amount of white light which was left when she abstracted from the colored light its color component.

W. utilized three different criteria. During the work on the first pair of colors, blue and yellow, she used the "nearness" standard. The color which looked farther away was called darker, and when subjective equality was reached they appeared to stand side by side. This seemed unsatisfactory, as the experiment proceeded, so she changed to the luminosity standard described above. With this she judged blue and green and green and yellow, in dark adaptation. Up to this point she felt that, although she was guiding herself by the luminosity criterion, she might have arrived at the same result with the other. At this point, the criteria separated, so that she must, perforce, choose one or the other, or adopt a third. She selected a new standard which she called "the amount of whiteness per unit of color" and used it for the remainder of the tests. She felt better satisfied with this than with either of the others.

We are unable to make, with our subjects, a correlation between criterion used and type of results which followed. F. and W. were the only ones who employed the whiteness criterion, which with Langfeld's subjects made the results very dark. In neither of our cases do we find this true. F.'s curve usually holds a conservative middle ground among those of the other subjects, and wherever W.'s curve departs from the mean it is brighter rather than darker. This difference between the results from two criteria should be worked out more fully, for it may prove to be a distinction of value.

The subjects frequently differed widely one from the other in respect to their brightness judgments. But when an individual was required to repeat a series which he had completed at an earlier sitting, the results of the second test closely approximated those of the first. In all cases, the variability of the subjects from time to time was less than the differences which were being measured.

IV. RESULTS

(A) PRELIMINARY EXPERIMENTATION

The preliminary observation of the complete spectrum was made by all seven subjects, and also by several others. Three of the latter were trained observers and knew what to expect, while four were ignorant of the nature of the experiment. There was some variation of opinion as to the points of greatest brightness and darkness, but their judgments may be summarized in the following statements.

(1) Color changes

- (1) As the illumination diminished, yellow disappeared, followed by orange. Both persisted as brightness for a short period after the color was gone.
- (2) Blue and green lost their color, but persisted as brightness for a considerable period before disappearing altogether.
- (3) Red retained its color at the lowest intensity (No. 3) when all other colors had disappeared. It did not show the brightness interval which the other colors displayed after their color tone was lost.
- (4) The subjects did not report the phenomenon described by Ebbinghaus (13) that in the lower intensities red, green, and violet lie contiguous to one another, having obliterated the intermediate colors. There seemed to be, in the lower stages, a distinct gap in the spectrum where the yellow and the orange originally lay.

(2) Brightness changes

- (1) When the spectrum was at full illumination, (No. 1), the choice of the brightest point ranged from greenish yellow to a yellow which was very near orange.
- (2) With the spectrum at full illumination, the darkest point was in the violet.

(3) With decreasing illumination, the brightest point in the spectrum gradually shifted from yellow toward green, until at the lowest intensity the points chosen as brightest by the various observers ranged from pure green to bluish green.

(4) The darkest point, at the lowest intensity, lay in the red. Yellow and orange were entirely gone.

(5) The observers spoke of the brightness shift as a very vivid thing. Particularly when it reached the middle of the pure green, the color shone out with great brilliancy as compared with the surrounding colors. "It fairly jumps out at one," several said. The same exclamation was made during a rough test of this kind with colored papers.

(6) The reverse of the above brightness shift was brought about by increasing the illumination from stage No. 3 up to No. 1. The point at which yellow suddenly became brighter, which occurred shortly before No. 1 was reached, was marked by a startling accession of brightness.

The results given above are not strictly comparable with our later experiments, because although the subject's eyes were dark-adapted for a few minutes, the adaptation was in no sense as complete as that used in the dark series.

(B) MAIN EXPERIMENTATION

(*1*) *Color changes*

In dark adaptation, certain color changes were observed. In stages No. 1 and No. 2, all the lights were recognizable as color, though in some cases the color quality had changed in No. 2. The subjects were unanimous in reporting that all colors except red had lost their color tone at No. 3, and appeared only as brightness. In every instance, red was reported as still retaining some color, however faint. Theoretically, all the colors of a pure spectrum are as saturated as possible, but the subjects spoke continually of apparent differences in

saturation. This was the case with red, which was described as an extremely saturated color in the highest illumination, "like the bottles in a drug store window," and at all stages seemed to retain its saturation more than the others.

Yellow is described by several as being whitish and unsaturated, and at No. 3 is spoken of as pure white. This differs from the judgments upon the entire spectrum reported in an earlier paragraph, for in those, the yellow is reported as having disappeared entirely, leaving a gap. It must be remembered that, in the latter case, adaptation was far from complete. Also the white valence of yellow is comparatively small, so when it is observed with the partially dark-adapted eye, it is possible that the sensitivity of the eye is not great enough to allow it to be affected by this small amount of white valence. On the other hand, when the eye is completely dark-adapted, it is sufficiently sensitive to allow the white valence of yellow to affect it.

Most of the observers spoke of green in the highest illumination as rather saturated, though not so much so as red. A strange phenomenon took place in the green during the diminishing of the light intensity, namely, the tendency to appear blue in tone. This was spoken of with surprise by nearly all the subjects. The color would be decidedly green at No. 1, but at No. 2 it usually appeared as blue. Such accounts as these occurred in the introspections. "In No. 1 we had a good green but when it was cut down to No. 2 it was a pale blue. I do not understand this." "The color at the right at No. 2 (he did not know what pair was being used) is a pale blue." "The right-hand color (green) looks bluish." "Cutting down the intensity of the green makes it look like blue. In no case did green appear blue at No. 1, but it did so frequently at No. 2. At this stage green appeared bluish or as blue in 13 out of 18 cases. We cannot ascribe this fact to contrast or to the influence of the other color in the combination, for it occurs in cases in which green is compared with each of the other colors.

Blue is often characterized as "a dull color," also as "rather whitish." At No. 2, blue is reported as looking like violet 5 times out of 18. This seems to be a parallel case with the tendency of green to appear blue.

The light adaptation series does not differ materially from the dark adaptation as regards changes in color quality. For instance, at stage No. 2 green appears as blue in 15 cases out of 18.

These changes in color quality which come with decreased illumination are puzzling. We are in possession of no like data from the literature of the subject, with the exception of Purkinje's remark that with the oncoming of dawn green appears bluish, and that its yellow tint first develops when daylight is well advanced. It is also known that if a green disc is mounted on a color wheel and mixed with black, the resulting color is bluish in tone. These changes cannot be phenomena of adaptation, because they appear in both the dark- and the light-adapted series.

(2) *Brightness changes*

(a) Explanation of tables

We now pass to a discussion of the brightness changes which occurred under our experimental conditions. Our results are set forth in four tables giving the numerical value of the comparative brightnesses and also the mean variation and the average deviation. These tables are supplemented by twenty-six sets of curves in which the results are put into graphic form for greater ease in reading.

The tables are constructed in the following manner. For each subject there are four standard colors, red, yellow, green, and blue. Each of these is compared with each of the others at the different light-intensities, and in both dark and light adaptation.

The tables are to be read from left to right, the first column indicating the standard color. The comparison colors appear at the top of the columns of figures. These figures represent

TAB

LIGHT AI

Standard Color	Light Intensity	A R	A Y	A G	A B	C R	C Y	C G	C B	F R	F Y	F G
R	No. 1		210	297	−292		190	149	− 67		214	131
	No. 2		175	300	−318		173	181	−135		179	18[illegible]
Y	No. 1	−150		180	−126	−170		−229	− 42	−146		−26[illegible]
	No. 2	−185			−146	−187		−227	− 64	−181		−31[illegible]
G	No. 1	− 63	−180	199	−143	−211	131		− 55	−221	134	
	No. 2	160	−161		−139	−179	133		− 71	−172	43	
B	No. 1	158	244	217		293	318	305		247	317	28[illegible]
	No. 2	42	214	221		225	296	289		175	239	25[illegible]
	Average Deviation	4.5	7.2	3.9	5.5	2.5	2.2	4.0	2.0	13.5	6.5	11.0
	Mean Variation	5.0	7.2	6.5	5.5	5.1	4.8	5.0	3.5	8.8	6.1	6.9

-E II

APTATION

	H				P				W			
B	R	Y	G	B	R	Y	G	B	R	Y	G	B
−113		− 55	−226	− 94		138	−163	− 87		−238	223	−122
−185	105	−323	−298	−179		190	−256	−122		−216	211	−237
− 43	− 37		−183	− 53	−222		−209	− 47	122		−169	− 82
−121	134		−238	− 62	−170		−268	− 67	−144		−132	−100
− 72	62	177		− 69	197	151		− 51	−137	191		−103
−105	266	132		− 70	104	92		− 52	−149	228		−102
	181	307	291		273	313	309		238	278	257	
		298	290		238	293	308		123	260	258	
6.9	9.8	9.7	7.6	8.2	2.2	4.5	6.5	2.1	4.5	7.2	5.1	6.5
5.2	4.2	3.7	4.4	4.0	8.2	6.5	5.9	3.3	6.2	6.0	6.9	5.6

the number of degrees which must be cut off from the comparison light (by closure of the episcotister) in order to make it appear of the same brightness as the standard. We have put the results in these terms because the curves made on this basis are more easily read. Therefore, the number of degrees of colored light required to match the standard in brightness may be obtained by subtracting the number in the table from 360. Figures with a minus sign before them represent the case in which the comparison light is no longer brighter than the standard. Thus it is necessary to reduce the brightness of the standard color to make it equal to that of the comparison color.

TABLE III

Comparison of Foveal and Peripheral Judgments of a Pair of Colors. Dark Adaptation

Subject	St.	Comp.	Judgments	No. 1	No. 2	No. 3
A	G	Y	Fov	−183	−159	−173
			Per	0	−186	−139
C	R	Y	Fov	242	257	316
			Per	211	218	314
F	R	B	Fov	−128	196	318
			Per	274	333	331
H	B	G	Fov	303	259	197
			Per	179	198	186
P	B	Y	Fov	306	250	92
			Per	172	−136	−187
W	G	R	Fov	− 17	− 24	− 12
			Per	− 33	− 48	− 12

To illustrate the way in which the tables are to be read, take, for example, the first line in Table I.

	Y	G	B
R No. 1	229.0	267.0	288.0

This means that the test is made at light-intensity No. 1, that red is the standard, and that to make the colors equal to red in brightness it is necessary to add to yellow 229° of unstimulated area (the closed sections of the episcotister), to green 267°, and to blue 288°. The first line in the yellow group, however, is different.

	R	G	B
Y No. 1	−131.0	177.0	−131.0

TABLE IV

SUMMARY SHOWING COLORS CHOSEN AS BRIGHTEST AND DARKEST POINTS IN THE SPECTRUM. DARK AND LIGHT ADAPTATION

		Number of times each color was chosen as brightest (out of a possible 24)		Number of times each color was chosen as darkest (out of a possible 24)	
	St.	DARK	LIGHT	DARK	LIGHT
No. 1	R	0	4	6	5
	Y	14	16	1	3
	G	9	4	5	5
	B	1	0	12	11
No. 2	R	0	4	8	4
	Y	3	12	3	4
	G	20	8	0	6
	B	1	0	13	10
No. 3	R	0		12	
	Y	0		10	
	G	23		0	
	B	1		2	

Since the red and the blue results are preceded by minus signs, we understand that both red and blue are less bright than the standard yellow. Therefore, either red and blue must be brightened, or yellow must be darkened, which comes to the same thing in the end. Because it can be done more accurately, the yellow has been cut down. Then to match the blue and the red in brightness it is necessary to reduce the yellow from 360° to 131° by adding 229° of unstimulated area.

(b) Explanation of curves

The curves are drawn in such a way that all points above the axis of abscissæ represent the number of degrees which must remain unstimulated in the comparison light (closed area of episcotister) in order to make it appear equal in brightness to the standard. All points below this line represent the number of degrees of the standard color which are required to make it as bright as the comparison. All results marked in the tables with a minus sign lie below the line, the others above it. Thus the highest point in the curve represents the brightest point and the lowest represents the extreme lack of brightness. The ordinates of these curves are the points at which the Frauenhofer lines cut the spectrum. Each subject is represented in all the plates by an individual graph.

(c) Comparison of the results for the six subjects

It is unnecessary to go over the results point by point, showing how the curve of one subject compares with that of another. An examination of the curves themselves will be more enlightening than many paragraphs. But the consistency of the judgments may be summarized in a few words.

In the dark adaptation series the consistency of the six subjects was as follows: for red, No. 1, poor; No. 2, fair; No. 3, extremely good: for yellow, No. 1, good with two exceptions; No. 2, fair; No. 3, good, with one exception: for green, No. 1, poor; No. 2, fair; No. 3, good, with one exception: for blue, No. 1, good, with two exceptions; No. 2, fair; No. 3, good, with

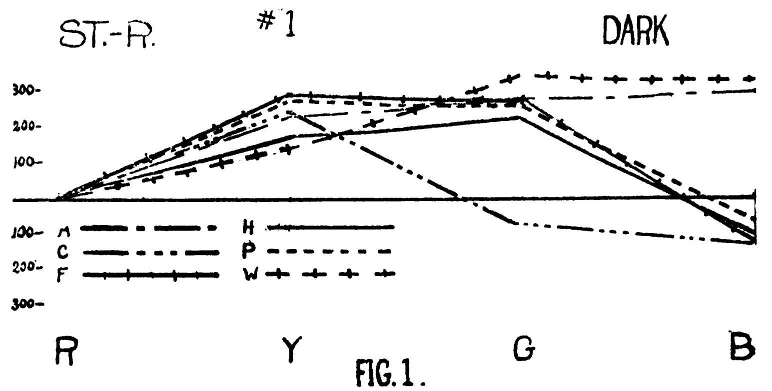

FIG. 1.

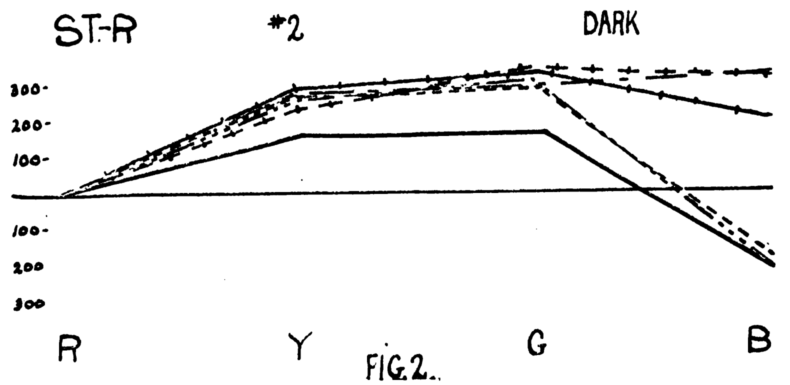

FIG. 2.

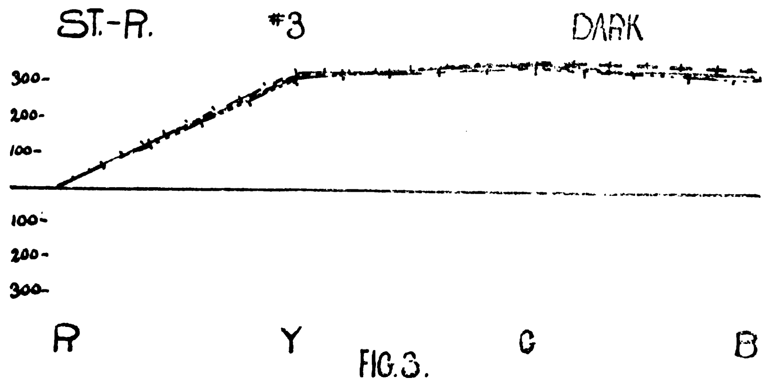

FIG. 3.

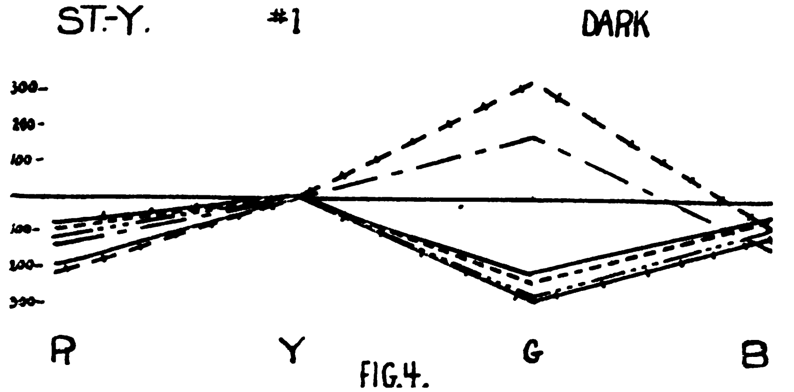

FIG. 4.

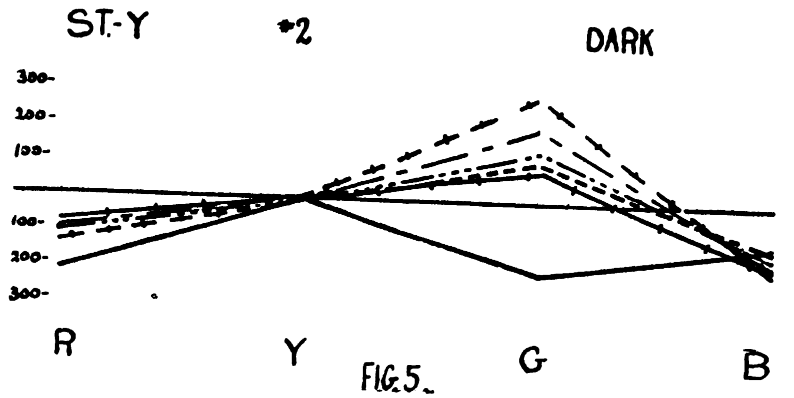

FIG. 5.

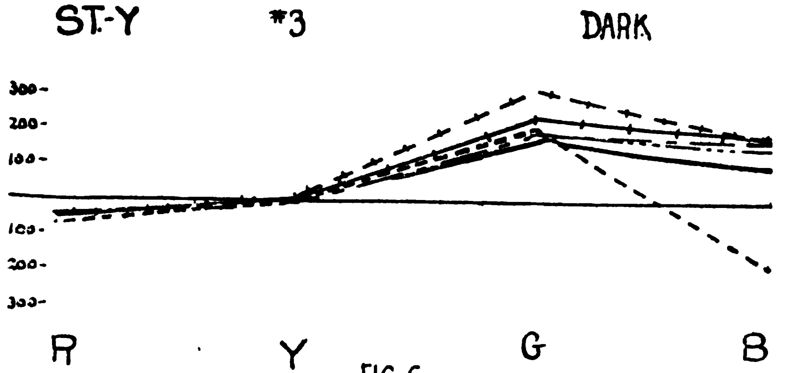

FIG. 6.

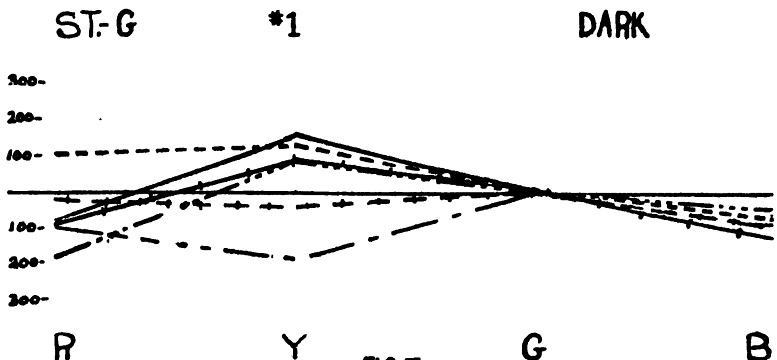

FIG.7.

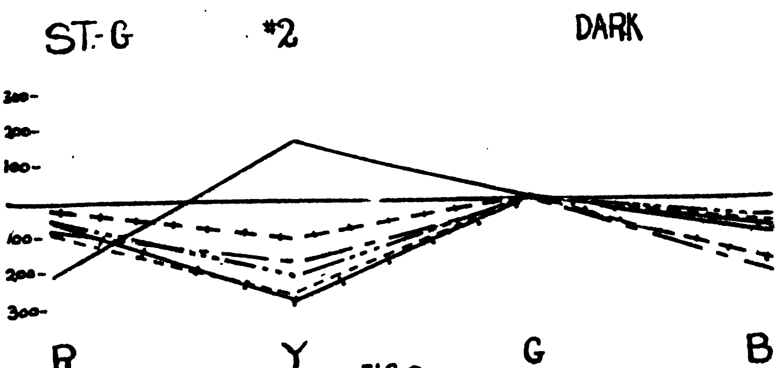

FIG.8.

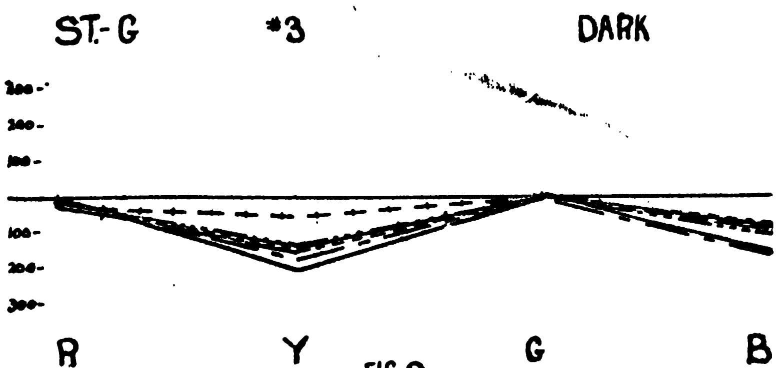

FIG.9.

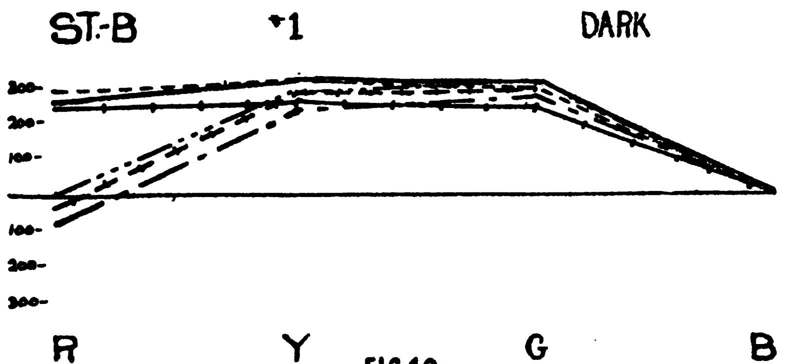

FIG. 10.

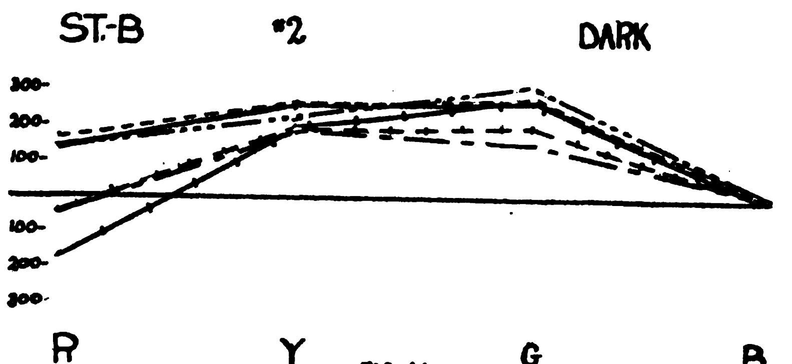

FIG. 11.

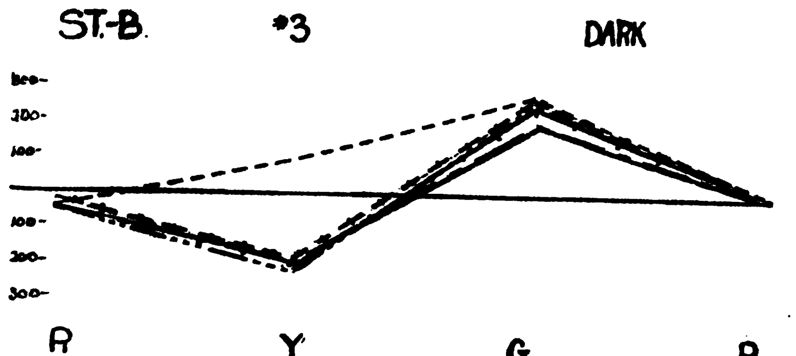

FIG. 12.

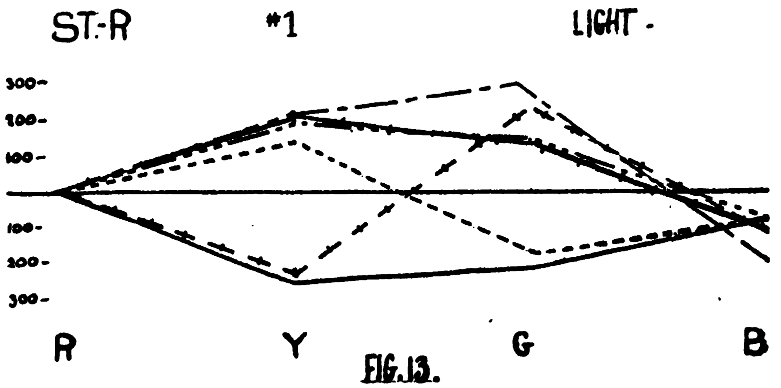
ST:-R
#1
LIGHT -
300-
200-
100-
100-
200-
300-
R
Y
G
B

FIG. 13.

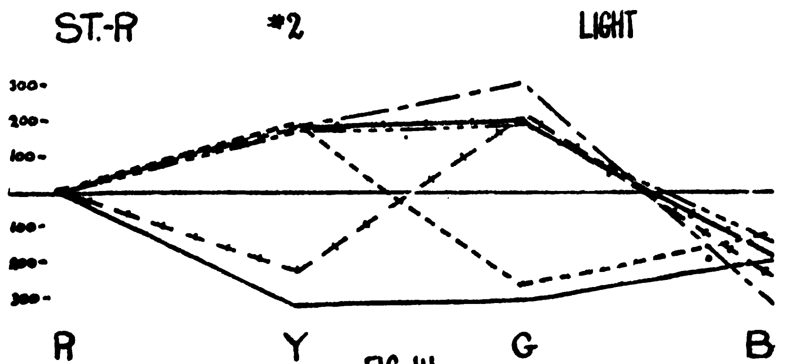
ST.-R
#2
LIGHT
300-
200-
100-
R
Y
G
B

FIG. 14.

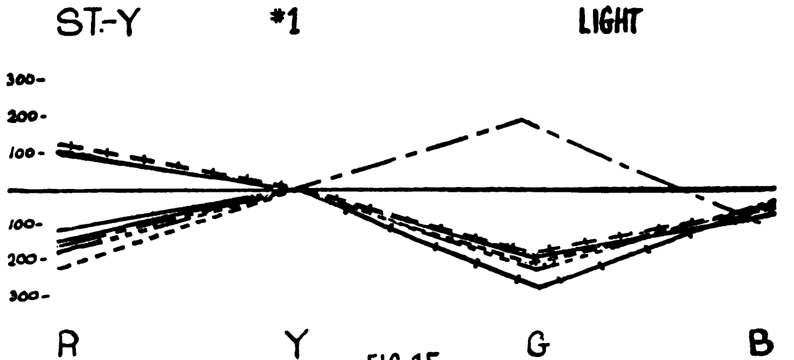
ST-Y
#1
LIGHT
300
200
100
100
200
300
R
Y
G
B

FIG. 15.

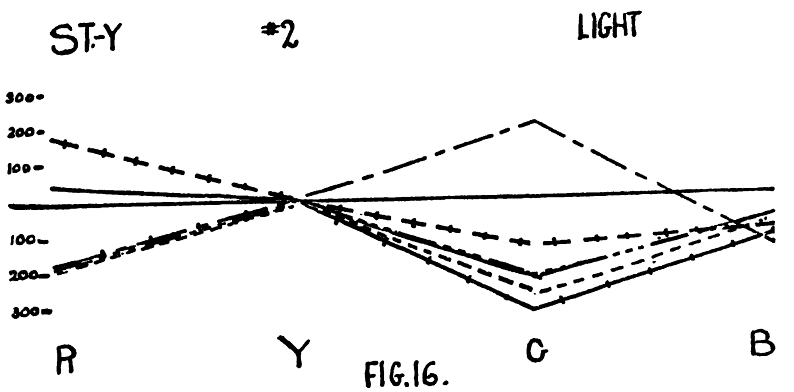
ST-Y
#2
LIGHT
300
200
100
100
200
300
R
Y
G
B

FIG. 16.

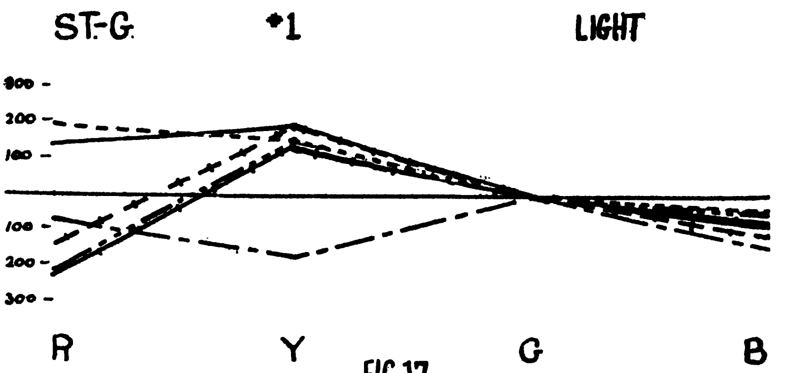
ST.-G.
*1
LIGHT
300 -
200 -
100 -
100 -
200 -
300 -
R
Y
G
B

FIG. 17.

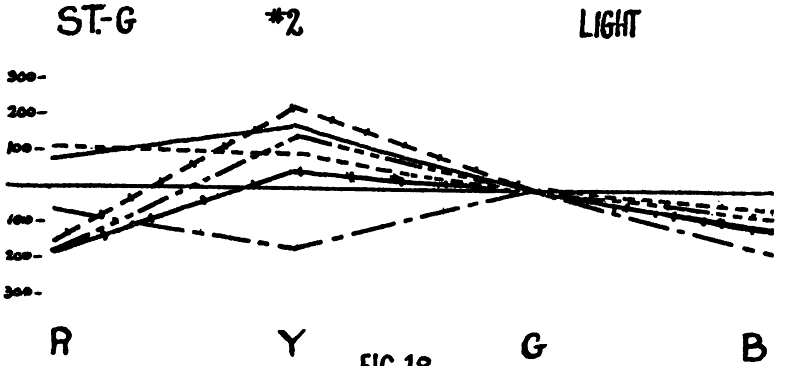
ST.-G
*2
LIGHT
300-
200-
100-
100-
200-
300-
R
Y
G
B

FIG. 18.

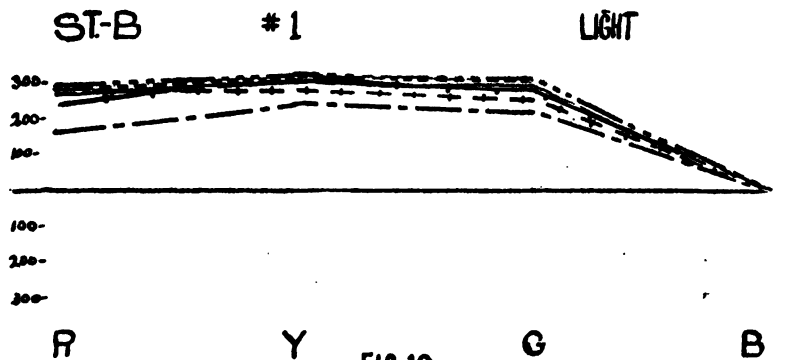
ST-B
#1
LIGHT
300-
200-
100-
100-
200-
300-
R
Y
G
B

FIG. 19.

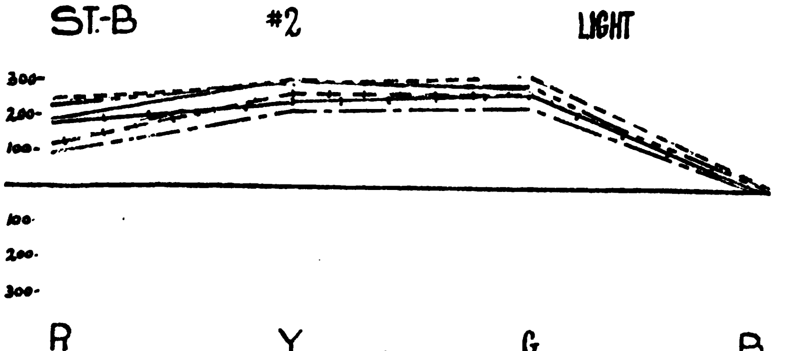
ST-B
#2
LIGHT
300-
200-
100-
100-
200-
300-
R
Y
G
B

FIG. 20.

one exception. In general, the consistency at No. 1 was irregular, at No. 2 it was fair, and at No. 3 quite uniformly good.

At stage No. 2 of the light adaptation series there is more variation among the subjects than at No. 1 of the same series. This greater variation may perhaps be attributed to the changed relations between the strength of the lights and the strength of daylight illumination.

(d) Results in central vision

In summing up the results for dark adaptation, we may say:

1. At No. 2 the Purkinje phenomenon has begun to be operative, to a certain extent.

2. In decreasing illumination, green tends to show the phenomenon before it appears in blue.

3. The same pair of colors, at the same light-intensity, displays the Purkinje phenomenon completely for some subjects, while it is only partially in evidence for others.

4. At No. 3 most of the subjects obtain the phenomenon in its typical form, with the brightnesses of all colors differing from those at No. 1, and with green as the brightest color, followed by blue.

5. Certain subjects do not experience the phenomenon at all, or only in one pair of colors.

In the light adaptation series there is much variation, but on the basis of the results in hand, we can say only that at No. 2, decrease of light-intensity, with the dark-adapted eye tends to produce the phenomenon, while decrease of light-intensity with the light-adapted eye does not produce it. Our results partially confirm those of Hering (22).

(e) Comparison of curves for dark and light adaptation

We must now compare the shape of the curves at stage No. 1 in dark adaptation with those for the same intensity in light adaptation. There is a possibility that the spectrum at this intensity, seen with the dark-adapted eye, may show tendencies toward the Purkinje phenomenon, as compared with the same spectrum seen with light adaptation. Should this prove true, we might assume that the very fact of adaptation, without

reduction of the light-intensity of the colors themselves, had started the phenomenon. A glance at the curves, however, shows that this is not the case. Those for three of the subjects are of approximately the same shape for both the dark and the light series. The others vary greatly, and there is no evidence of the phenomenon in the comparison.

On the other hand, a comparison of the judgments at stage No. 2 in dark and light adaptation yields different results. The dark adaptation series shows the Purkinje phenomenon in 26 cases out of 36, while the light adaptation results display it in 2 cases out of 36. In both series the same decrease in light-intensity takes place, and the only variable factor is the state of adaptation. Results seem to point to the condition of dark adaptation as playing a very important part in the production of the phenomenon at this light-intensity. But we have seen in the preceding paragraph that at No. 1 dark adaptation alone seems ineffective to bring about such a result, and we have also seen that decrease of light-intensity alone, without dark adaptation, seems not to accomplish that end. These both lead us to the conclusion that the Purkinje phenomenon is the result of a decrease of light-intensity during a condition of complete or partial dark adaptation of the retina.

(c) PERIPHERAL SERIES

In order to discover whether or not the absence of the colored component makes any difference in the brightness judgments at the three intensities in dark adaptation, we tried a series with peripheral judgments. Tests were made with one pair of colors in peripheral vision by each subject, by the use of the device described in the section on method. Just prior to the making of these judgments, a part of the corresponding foveal series was repeated, in order to make sure that the latter was accurate enough to be used as a basis of comparison. In every case except one, the second foveal series was sufficiently like the original one to warrant the use of the original in the comparative table. The results are set forth in Table III and Figures 21 to 26.

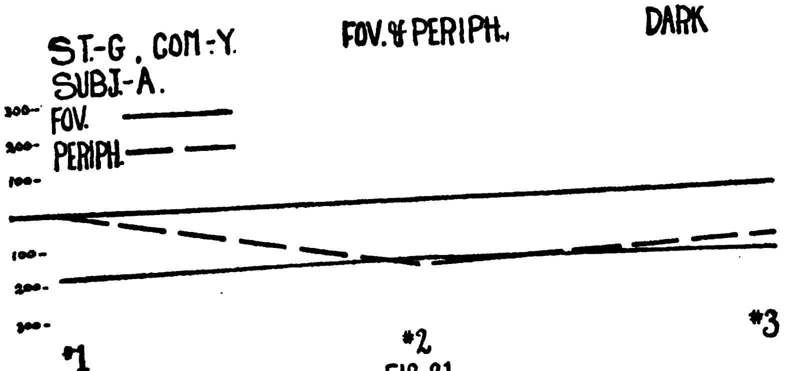

FIG. 21.

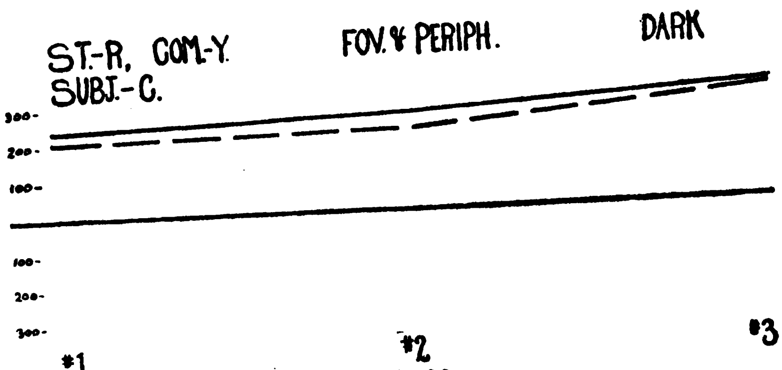

FIG. 22.

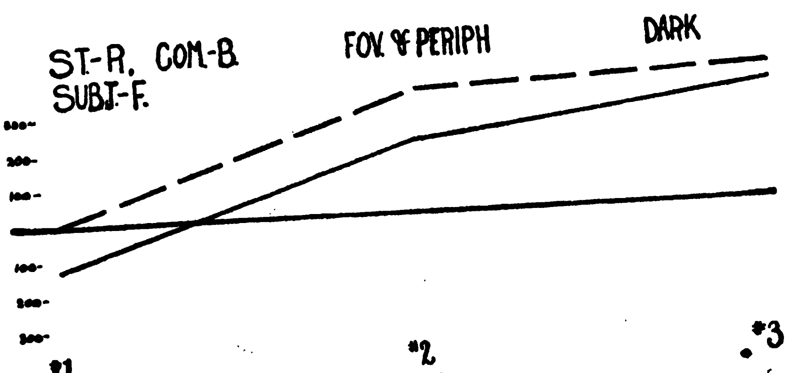

FIG. 23.

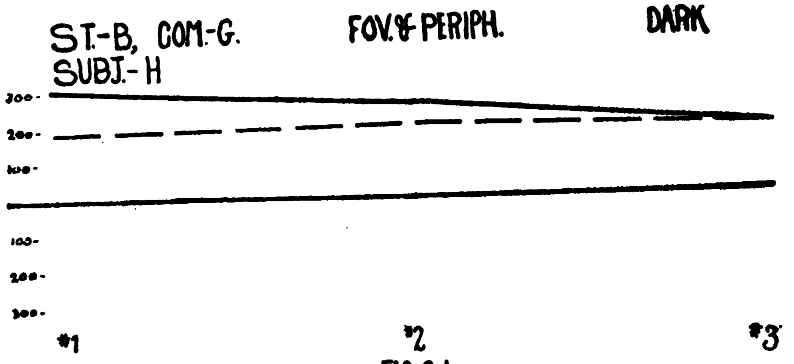

FIG. 24.

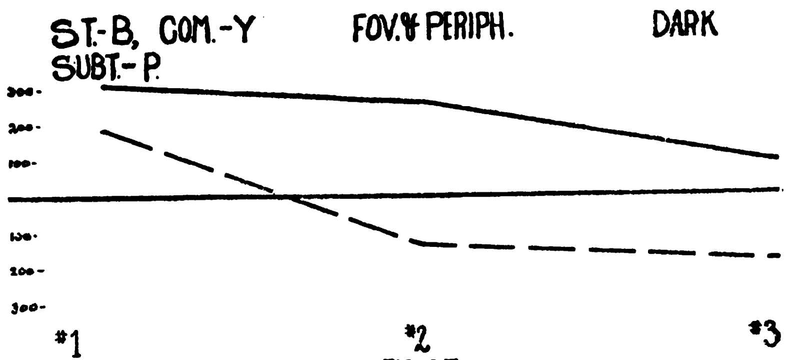

FIG. 25.

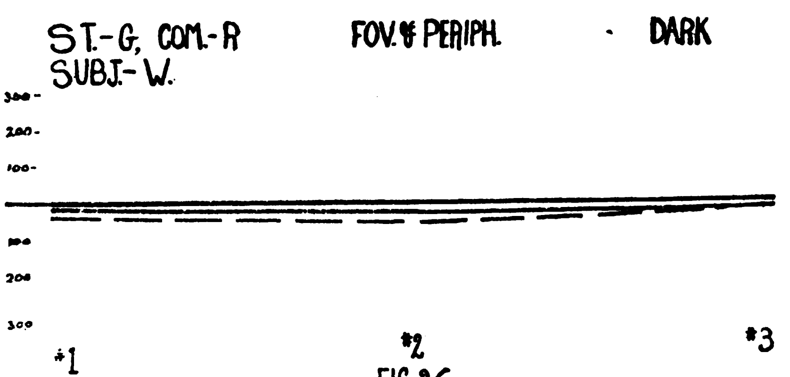

FIG. 26.

On account of the shape and size of the pupil of the eye, the structure of the retina, and other conditions, a pencil of rays moving out from the fovea to the periphery is gradually decreased in intensity just as truly as though it were cut down with an episcotister. For this reason, judgments at stage No. 1 in center and periphery are not strictly comparable. A peripheral judgment, as contrasted with a central judgment at No. 1 is made under the conditions which we have previously laid down for the phenomenon, namely, decrease of light-intensity and dark adaptation of the retina. Then some trace of the phenomenon ought to be discovered between No. 1 in the dark adaptation series and No. 1 in the light adaptation series. In the results of 5 subjects at stage No. 1, this proves to be the case. C. and P. show yellow judged as duller in the peripheral series, while for C. red is brighter than yellow and for P. blue is brighter than yellow. W. finds green brighter than red in the periphery, while F. makes blue bright and red dull under the same circumstances. For A. the peripheral green is brighter than the yellow. H. is the only exception, for he finds blue brighter than green in the periphery. Then the conditions laid down for the Purkinje phenomenon seem also to hold good in the case of colors decreased in light-intensity by moving them toward the periphery of the retina.

V. CONCLUSIONS

1. Factors involved in the production of the Purkinje phenomenon
    a) A sufficient decrease in the light-intensity of spectral colors, with the eye in a condition of dark adaptation, is accompanied by the Purkinje phenomenon.
    b) Decrease of light-intensity without dark adaptation of the eye is not, as a rule, accompanied by the phenomenon.
    c) Dark adaptation of the eye, without adequate decrease of light-intensity of the colors is not accompanied by the phenomenon.
2. Brightness comparisons
    a) Judgments upon the comparative brightnesses of markedly different colors are difficult to make, and subjects feel uncertain about them.
    b) Judgments made at the beginning of any series tend to serve as models for those which follow in the same series.
    c) In spite of this variability in judgments, the Purkinje phenomenon appears under the conditions named in Conclusion 1.
3. Brightness criteria
    a) Subjects use three criteria in judging the comparative brightness of two colors:
        1. Luminosity (the illuminating power of the colors);
        2. Whiteness (the amount of white light which is left when the colored component is mentally abstracted from a colored light);
        3. Distance (the apparent distance of the color from the eye of the observer).[1]

[1] Langfeld's "solidity" standard (p. 24) may be added to this list.

b) No correlation could be made between the type of criterion employed and either the accuracy or the character of the results obtained.

4. Color changes
   a) Dark adaptation
      1. At the two higher stages of light intensity which were employed in the experimentation, all lights were recognized as colored, as distinguished from white.
      2. At the lowest stage of light-intensity all colors except red had lost their color tone and appeared as pure brightness. Red held its color until the light disappeared altogether.
      3. Green appeared bluish at the middle stage of light-intensity in 13 cases out of 18, as green in 2 cases, 3 cases unreported.
      4. At the middle stage, blue appeared as violet 5 times out of 18. It appeared as blue 13 times.
   b) Light adaptation
      1. At the two higher light-intensities, all lights were recognized as colored, as distinguished from white.
      2. Green appeared as blue 15 times, as green once, no report in 2 cases.
      3. Blue appeared as violet twice, as green once, as blue 15 times.
5. Brightness changes
   a) Dark adaptation
      1. The brightest point in the spectrum tends to shift from yellow to green with decreasing light-intensity. Blue increases greatly in brightness.
      2. The darkest point in the spectrum tends to shift from blue to yellow and red, with decreasing light-intensity.
      3. Occasionally green appears as the brightest point, at the highest light-intensity. In such cases its relative brightness is increased with the

decreasing of the light-intensity, while the other parts of the spectrum behave normally.

b) Light adaptation

1. The tendency is to choose yellow as the brightest point in the spectrum at the highest light-intensity.
2. The tendency is for yellow to remain the brightest point when the light-intensity is decreased.

c) A given pair of colors, at the same grade of light-intensity and under conditions of light adaptation, display the phenomenon complete for certain subjects, while it is entirely absent or only partially operative for others. This may be due to differences in the sensitivity of the retinae of these persons.

6. Critical point

a) At the middle stage of light-intensity, and under conditions of dark adaptation, the Purkinje phenomenon has only partially appeared. Some subjects do not report it at this stage, others observe it in green alone. A few report it in green and blue, with a concomitant darkening of yellow and red. None report it in the blue alone.

7. Peripheral vision

a) Moving the images of colored lights onto the periphery of the retina constitutes in itself a decrease of light-intensity. When this is done under conditions of dark adaptation, the conditions for the Purkinje phenomenon are fulfilled and it appears without objective diminution of the light-intensity.

b) Decreasing the objective light-intensity of colors when viewed peripherally, slightly intensifies the Purkinje phenomenon which was brought out by moving the image to the periphery. This change is much less marked than that which takes place when the light-intensity is decreased under conditions of central vision.

BIBLIOGRAPHY

1. Aubert, H. Grundzüge der physiol. Optik. Leipzig, 1876.
2. Aubert, H. Physiol. der Netzhaut. Breslau, 1865.
3. Baird, J. W. The Color Sensitivity of the Peripheral Retina. Carnegie Institute of Washington, 1905.
4. Brodhun, E. Beiträge zur Farbenlehre. Inaug.-Dissert. Berlin, 1887.
5. Burch, G. J. On Color Vision by Very Weak Light. Proc. Royal Soc., 76 B, 1905, 199-216.
6. Charpentier, A. L'adaptation rétinienne et le phénomène der Purkinje. Arch. d'Ophthal., 16, 1896, p. 188-195.
7. Chodin, A. Ueber die Abhängigkeit der Farbenempfindung von der Lichtstärke. Sammlung phys. Abhandl. von W. Preyer, I. 7, 1877, S. 1-66.
8. Dobrowolsky, W. Ueber die Empfindlichkeit des Auges gegen die Lichtintensität verschiedener Spectralfarben. Arch. f. Ophthal. (von Graefe's) 18, 1, 1872, S. 74-92.
9. Dobrowolsky, W. Ueber die Empfindlichkeit des Auges gegen verschiedene Spectralfarben. Arch. f. Ophthal. (von Graefe's) 18, 1, 1872, S. 66-74.
10. Dobrowolsky, W. Ueber gleichmässige Ab- und Zunahme der Lichtintensität verschiedener Spectralfarben bei gleichmässiger Ab- und Zunahme der Lichtstärke des Gesammtlichtes. Arch. f. Ophthal. (von Graefe's) 18, 1, 1872, S. 92-98.
11. Dobrowolsky, W. Ueber die Veränderung der Empfindlichkeit des Auges gegen Spectralfarben bei wechselnder Lichtstärke derselben. Archiv. f. d. ges. Physiol. (Pflüger's) 24, 1881, S. 189-202.
12. Dove, H. Ueber den Einfluss der Helligkeit einer weissen Beleuchtung auf die relative Intensität verschiedener Farben. Pogg. Ann. 85, 1852, S. 397-408.
13. Ebbinghaus, H. Grundzüge der Psychologie. Leipzig, 1897-1902.
14. Eisenmeier, J. Untersuchungen zur Helligkeitsfrage. Halle a. S., Niemeyer, 1905. S. 66.
15. Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev. Monograph Supp. X. No. 3, 1909.
16. Fernald, G. M. The Effect of Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision. Psychol. Rev., 12, 1905, 386-425; 15, 1908, 25-43.
17. Fick, A. E. Studien über Licht- und Farbenempfindung. Archiv. f. d. ges. Physiol. (Pflüger's), 43, 1888, S. 441-501.
18. Frauenhofer, J. Denkschriften der bayrischen Akad., 5, 1817, München. S. 193.
19. Grailich, J. Beitrag zur Theorie der gemischten Farben. Sitzungsber. der kaiserl. Akad. der Wiss. zu Wien., 13, 1854, S. 201-284.

20. Gruber, E. Experimentelle Untersuchungen über die Helligkeit der Farben. Philos. Studien (Wundt), 9, 1894, 429-446.
21. Helmholtz, H. von. Handbuch der physiologischen Optik. Aufl. II, Leipzig. 1896, S. 428-446.
22. Hering, E. Ueber das sogenannte Purkinje'sche Phänomen. Archiv. f. d. ges. Physiol. (Pflüger's) 60, 1895, S. 519-542.
23. Hering, E. Ueber Holmgren's vermeintlichen Nachweis der Elementarempfindungen des Gesichtssinns. Archiv. f. d. ges. Physiol. (Pflüger's) 40, 1887, S. 1-20.
24. Hering, E. Untersuchung eines total Farbenblinden. Archiv. f. d. ges. Physiol. 49, 1891, S. 563-608.
25. Hillebrand, F. Ueber die specifische Helligkeit der Farben. Sitzungsber. d. k. Akad. in Wien, Math-Nat. Classe, Bd. 98, 3, 1889, S. 70-120.
26. Kirschmann, A. Die Farbenempfindung im indirecten Sehen. Philos. Stud. (Wundt), 8, 1893, S. 592-614.
27. König, A. Die Abhängigkeit der Farben- und Helligkeitsgleichungen von der absoluten Intensität. Sitzungsber. der k. preuss. Akad. der Wiss. zu Berlin, 1897, (2) S. 871-882.
28. König, A. Die Abhängigkeit der Sehschärfe von der Beleuchtungsintensität. Sitzungsber. der. k. preuss. Akad. der Wiss. zu Berlin., 1897, S. 559-575.
29. König, A. Quantitative Bestimmungen an complementären Spectralfarben. Sitzungsber. der k. preuss. Akad. der Wiss. zu Berlin., 1896 (2), S. 945-949.
30. König, A. Ueber den Helligkeitswerth der Spectralfarben bei verschiedener absoluter Intensität. König's Abhandlungen zur physiol. Optik. S. 144. Also Beiträge zur Psychol. und Physiol. der Sinnesorgane. Helmholtz, 1891, S. 309-388.
31. König, A. Ueber den menschlichen Sehpurpur und seine Bedeutung für das Sehen. Sitzungsber. der k. preuss. Akad. der Wiss. zu Berlin., 1894, (2), S. 577-597.
32. König, A. Ueber Newton's Gesetz der Farbenmischung und darauf bezügliche Versuche des Herrn. E. Brodhun. Abhandlungen zur physiol. Optik. S. 108.
33. Koster. Untersuchung zur Lehre vom Farbensinn. Archiv. f. Ophthmal., 41, 4, S. 2.
34. von Kries, J. Der Purkinje'sche Phänomen. (Nagel's Handbuch.), S. 176-179.
35. von Kries, J. Ueber das Purkinje'sche Phänomen und sein Fehlen auf der Fovea Centralis. Centralbl. f. Physiol., 10, 1896, S. 1-3.
36. von Kries, J. Ueber den Einfluss der Adaptation auf Licht- und Farbenempfindung, und über die Function der Stäbchen. Naturforschende Gesellschaft z. Freiburg., I., Bd. 9, 1894, S. 61-67.
37. von Kries, J. Ueber die Farbenblindheit der Netzhautperipherie. Ztsch. f. Psychol., 15, 1897, S. 247-279.
38. von Kries, J. Ueber die functionellen Verschiedenheiten des Netzhautcentrums und der Nachbartheire. Archiv. f. Ophthal. (von Graefe's) 42, (3), S. 95-133.

39. von Kries, J. Ueber die Function der Netzhautstäbchen. Zeitsch. f. Psychol., 9, 1896, S. 81-123.
40. von Kries, J. und Nagel, W. A. Weitere Mittheilungen über die functionelle Sonderstellung des Netzhautcentrums. Zeitsch. f. Psychol., 23, 1900, p. 173-177.
41. Külpe, O. Outlines of Psychology. (Translated 1893 by E. B. Titchener.)
42. Ladd-Franklin, C. The Extended Purkinje Phenomenon. Psychol. Rev., 5, 1898, p. 309-312.
43. Ladd-Franklin, C. Hering's Theory of Color Vision. Nature, 48, 1893, p. 517.
44. Ladd-Franklin, C. On Theories of Light Sensation. Mind, N. S. II, 1893, p. 473-489.
45. Lamansky, Ueber die Gränzen der Empfindlichkeit der Auges für Spectralfarben. Archiv. f. Ophthalmol., 17, 1, 1871, S. 123-134. Also in Pogg. Ann. 143, 1871, S. 633-643.
46. Langfeld, H. S. Ueber die heterochrome Helligkeitsvergleichung. Zeitsch. f. Psychol., 53, 1909, S. 113-177.
47. Lépinay, J. Macé de, et Nicati. Recherches experimentales sur le phénomène de Purkinje. Journ. de physique (D'Almeida) Série II, 1, 1881, p. 33-39.
48. Levy-Suhl, M. Ueber die Helligkeitsverteilung im Spektrum für das helladaptierte Auge. Zeitsch. f. Psychol. 36, 1904. S. 74-89.
49. Martius, G. Ueber den Einfluss der Lichtstärke auf die Helligkeit der Farbenempfindungen. Beitr. zur Psychol. und Philos., 1, 1897, S. 161-171.
50. Newton, J. Optics. Bk. I, Pt. I, Prop. VII, Theorem VI.
51. Parinaud, H. La sensibilité de l'oeil aux couleurs spectrales. Revue scientifique, IV, 3, 1895, p. 709-714.
52. Peters, W. Die Farbenempfindung der Netzhautperipherie bei Dunkeladaptation und konstanter subjektiver Helligkeit. Archiv. f. d. ges. Psychol., 3, 1904, 354-387.
53. Pflüger, A. Ueber die Farbenempfindlichkeit des Auges. Annal. d. physic, 9(1), 1902, S. 185-208.
54. Piper, H. Ueber Dunkeladaptation. Zeitsch. f. Psychol., 31, 1903, S. 161-214.
55. Purkinje, J. Beobachtungen und Versuche zur Physiologie der Sinne. Bd. II. Neue Beiträge zur Kenntniss des Sehens in subjectiver Hinsicht. Berlin, 1825, S. 109-110.
56. Rice, D. E. Visual Acuity with Lights of Different Colors and Intensities. Columbia Contributions to Philos. and Psychol. XX, 2, 1912.
57. Rivers, W. H. R. Vision. In Schäfer's Text-book of Physiology, II, 1900, p. 1026-1148.
58. Sherman, F. D. Ueber das Purkinje'sche Phänomen im Centrum der Netzhaut. Philos. Studien. (Wundt), 13, 1898, S. 434-479.
59. Thompson, H. B. and Gordon, K. A Study of After-images on the Peripheral Retina. Psychol. Rev., 14, 1907, p. 122-167.
60. von Vierordt, C. Beschreibung einer photometrischen Methode zur Messung und Vergleichung der Stärke der farbigen Lichtes. Pogg. Ann., 137, 1869, S. 200-222.